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Deposition of conductive materials on textile and polymeric flexible substrates

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Abstract This paper describes the study, analysis and selection of textile and similar materials to be used as flexible substrates for thin conductive film deposition, in the context of integrating electronics into textiles. Kapton® polyimide was chosen as reference substrate material, was characterized regarding mechanical and electrical properties and was used as a basis for a comparison with several textile substrates. Samples were fabricated using physical vapour deposition (thermal evaporation) to deposit a thin layer of aluminium on top of Kapton and textile substrates. The measurement of electrical resistance of the thin aluminum films was carried out using the Kelvin method. To characterize the mechanical behaviour of the substrate and aluminum film, several mechanical tests were performed and results were compared between Kapton and these textile materials. The chemical composition of the textile substrates and aluminum films as well as the continuity of the films was characterized. This selection process identified the material that was closer to the behaviour of polyimide, a flexible, but non-elastic woven textile coated on both sides with PVC.

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1 Introduction

Applications in which the integration of microelectronics with textiles is necessary are usually achieved not by a true integration at textile structural level, but employing one of two approaches: sewing the microdevice, or hiding it in the textile structure [1–4]. Both approaches have specific implementation challenges. Sewing a micro device can be an easy task and acceptable on protection clothing, where comfort may be sacrificed in favour of functionality, but can be unfeasible for a sprinter suit where ergonomics and comfort are mandatory.

Textiles as substrates can be defined as microstructures with very interesting properties such as flexibility and mechanical stability. In spite of this, there is a slow development of techniques, processes and new materials to develop textiles as sensors, electrodes or as a part of a microelectronic device. This paper studies textiles as flexible substrates for conductive thin film deposition. The deposition of a conductive thin film directly on the textile allows direct electronic interconnections between the textile and electronic devices, enabling future applications such as antennas, pressure sensors and touch sensors.

In this work, polyimide was used as a reference material for conductive thin film deposition on flexible substrates, and comparison of the behaviour of textile materials with polyimide is presented.

Textiles are probably the material with which we interact more during our daily life. Although often we don't acknowledge them consciously during day-to-day interaction, they are one of the main materials of our surrounding environment.

The constantly growing demand for consumable electronics in the form of multimedia devices, next generation mobile phones and many other advanced gadgets is

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pushing a larger integration of these gadgets into daily life, unobtrusively and ubiquitously. The implementation of “smart clothes”, including wearable electronics, opens doors for a next level of integration, where user friendly interfaces and smart power management will allow clothes to offer additional functions such as integrated communications capability or vital functions monitoring. This fusion of textiles and electronics is normally designated as *E-textiles*. Among other applications, advanced telecommunications, advanced device control or medical devices can be considered as being dynamic areas of E-textiles research and development [5–7]. Protective clothes with wearable electronics can provide additional protection in hazardous environments or even provide navigation possibilities in open-air activities. With the constant shrinking and thinning of electronic devices, miniaturization of large electronic systems can be achieved in small silicon chips with multiple functions. The constant size decrease also allows easier integration in textiles and thus the creation of wearable electronics.

The integration of microelectronics with textiles represents a big challenge. The achievement of an effective integration demands a multidisciplinary approach of both electronic and textile industries. Processes for integration need to be robust and cost competitive. Materials selected for integration of electronics must be compatible with textile processes; usually they should be able to support high mechanical stress and have good endurance to daily wear. In an integration context these properties perform a role as important as the material’s electrical properties. From the textile side, properties and characteristics that can facilitate the interconnection with the electronic devices are an advantage. One of the integration techniques is the selective introduction of conductive yarns into the fabric through weaving or embroidering. These yarns are commercially available from several manufacturers of technical textiles and can be found based on materials such as copper, brass or aluminum wire [8], polymers or other materials coated with nickel, copper or silver [1, 9, 10], pyrrole or aniline [11] or stainless steel, pure or blended [9, 12]. Usually, the material of the conductive fibre is chosen according to the application in which it will be used, as all these materials have specific advantages and disadvantages. The main goal is to achieve a final fabric that should be close in characteristics to the main fabric matrix, whilst providing adequate electrical conductivity. If the electrical properties are well specified, this approach can be applied for signal transmission and power supply of the integrated devices [13–15]. One of the preferred materials for this kind of function is copper, mainly due to its high conductivity. Corrosion can be a problem specially if there is contact with water; to improve endurance, the copper fibres can be coated with either nickel or silver [16]. Electric contacts between the conductive fibres and the electronic device can be manufactured at the textile surface resorting to different techniques such as welding or conductive adhesives.

One of the main aspects to take into account regarding interconnection of textiles and electronics is the difference in size and flexibility between textiles and electronic devices. In order to adapt electronics to textiles regarding interconnection, several approaches can be used: development of specific chip carriers with long and flexible connection wires designed to be sewed to textiles [2], adapting semiconductor interconnection techniques between chip and PCB such as wire bonding [17] to the interconnection of conductive fibres on a fabric matrix. Flexible PCB’s (fPCB) can also be used and are usually made of polyimide. The fPCB can be interconnected with the textile by welding and the silicon chip can be normally wire bonded on the flexible PCB [18]. The flexible PCB can be replaced by ultra-thin and flexible packaging obtained from very thin wafers that can have thickness as low as 50 μm. At this thickness ranges, wafers become extremely thin and handling problems can arise during the interconnection processes [19–21]. Geometries for flexible interconnections designed to withstand high deformations are usually U- or horseshoe shaped and have been compared extensively in [22]. The use of separate redundant conductive lines instead of a single line design improves also the deformation that the interconnection can resist without reaching rupture.

2 Experimental

2.1 Substrate materials

Kapton® HN polyimide, with thickness of 50 μm, (from Dupont) was used as reference substrate material. This material is commonly applied on flexible electronic devices as a substrate [23]. It has excellent thermal stability in a range from −273 °C up to 400 °C and good dielectric properties [24, 25]. The conductive film material chosen for PVD deposition was aluminum due to its low electrical resistivity (2.8×10^{-8} ohm/m at 22 °C). Several different textile and similar flexible materials were investigated as possible substrates. In an initial stage of this work, it was found that to achieve deposition of aluminium, a continuous surface was needed. The materials presented in Table 1, investigated in this work, fulfil this requirement.

2.2 Deposition method

The thin film deposition process used in this work was physical vapour deposition by thermal evaporation. Sample preparation steps include cleaning the different substrate materials with IPA (Isopropyl alcohol) and drying them

Table 1 Textile flexible substrates material description

Reference material	Description
Sample A	Synthetic leather
Sample B	Natural leather
Sample C	Woven textile with PVC coating on both sides
Sample D	Woven textile with PVC coating
Sample E	Woven textile with PU coating
Sample F	Elastic knitted fabric with PU coating, matte

with nitrogen flow. Cleaned and degreased samples were then placed inside of the deposition chamber. Film thickness on the samples was around 300 nm, measured by a thin-film deposition controller. The process parameters are presented in Table 2.

The aluminium was deposited over the whole extension of the sample area. The objective was to analyse the conductive and mechanical properties of the sample/conductive layer combination.

2.3 Electrical characterization

Metals change their internal electric resistance when they are under strain; the relation between strain and electric resistance is given by the expression:

$$\left(\frac{\Delta R}{R}\right) = K.\varepsilon$$

where ΔR/R is the relative resistance variation and K is known as *gauge rate*, representing the sensitivity of resistance variation to strain ε. It can thus be stated that the electrical resistance variation is proportional to the strain suffered by the material. In order to characterize the electrical resistance variation under strain a dynamometer and a measurement setup using the Kelvin method (four probes) were used. The Kelvin method was selected by the need of getting accurate measurements of small resistance values. The Kelvin method imposes a current value to the measured resistance and measures the voltage at its terminals (see Figs. 1, 2).

The current flowing through the voltmeter is negligible compared to the current flowing through the measured resistance, and thus the voltage drop on the voltmeter's lead wires is insignificant.

Table 2 PVD deposition parameters

Base pressure	3.4×10^{-5}	mbar
Deposition rate	10	Å/s
Final thickness	300	nm
Deposition time	7	min

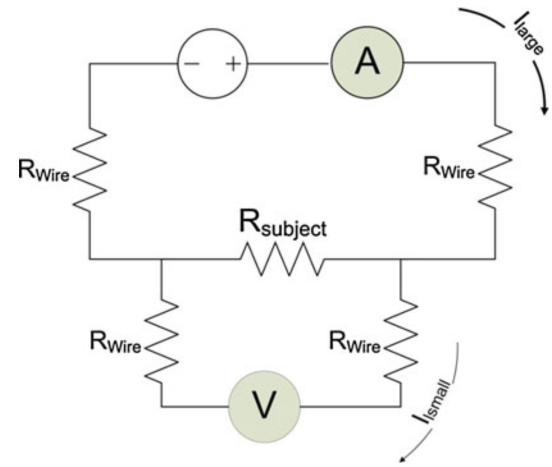

Fig. 1 Kelvin method measurement principle

2.4 Experiment plan

The experiments performed follow a set of steps in order to compare the reference substrate of Kapton with the textile materials. An additional characterization by SEM and EDX was performed on some of the textile samples in order to characterize the deposited film continuity and chemical composition.

1. A tensile test to rupture is performed to all materials in order to measure stress–strain curves. These samples are tested without any metal deposition;
2. From the stress–strain curves the yield strength is calculated for all materials;
3. Mechanical tests are performed on the elastic region of the substrate materials. Uniaxial cyclic tensile tests are performed on deposited samples with 300 nm thickness aluminium films;
4. During these tests electrical resistance variation is measured by Kelvin method;
5. From the electrical resistance variation the behaviour of the deposited film is evaluated. From analysis of the force–elongation curves during the cyclic test the behaviour of the substrate is evaluated;
6. The behaviour of the textile materials is compared to the results obtained on the Kapton substrates.

3 Results and discussion

3.1 Kapton

Kapton and textile samples were deposited with aluminum film (~300 nm) by PVD. Adhesion on the Kapton substrates was excellent and a continuous film was obtained. A

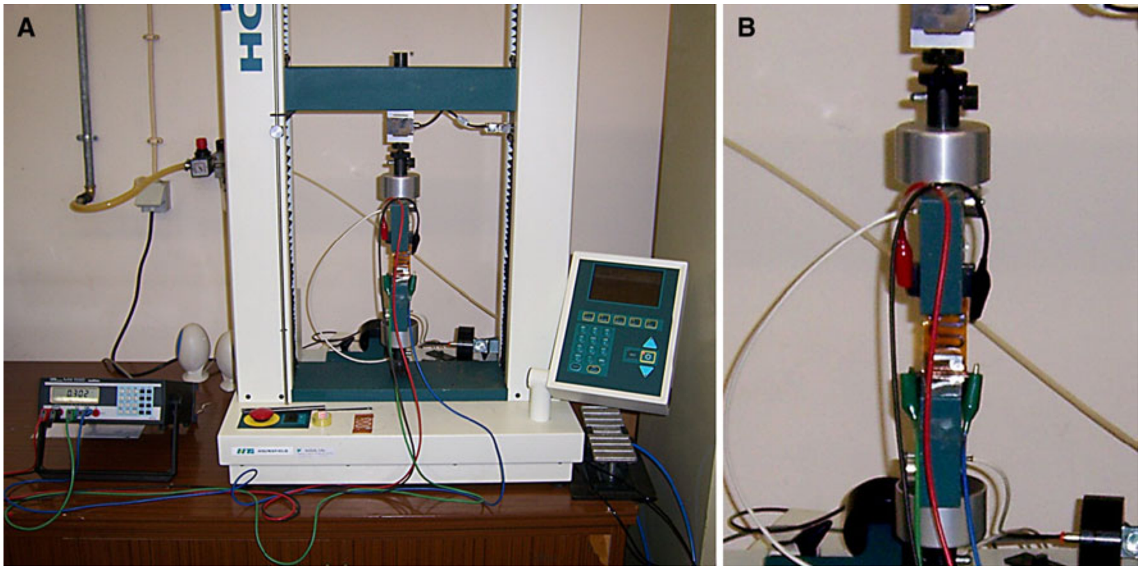

Fig. 2 Dynamometer with Kelvin method measurement setup, overview (**a**), connection detail (**b**)

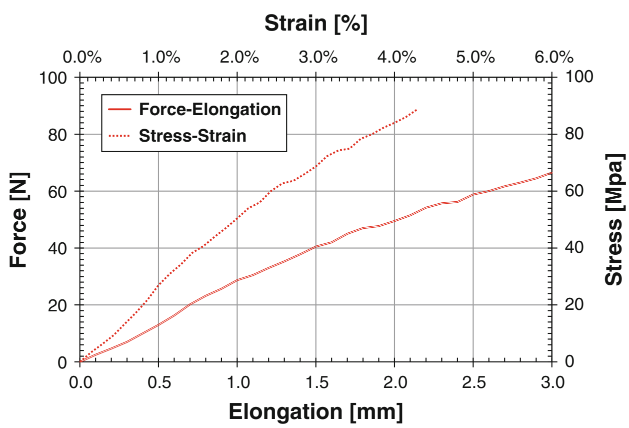

Fig. 3 Force/elongation–stress/strain curves

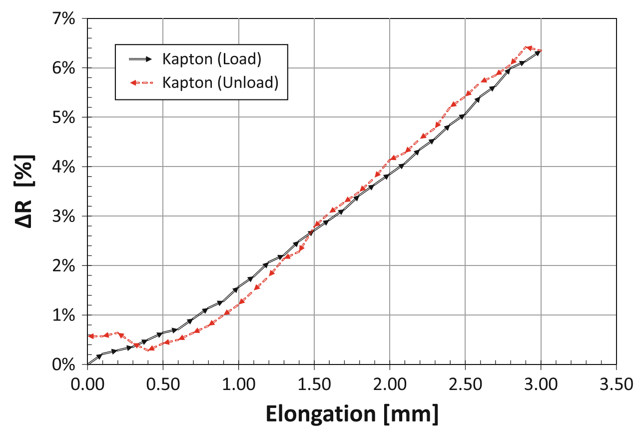

Fig. 4 Electrical resistance variation of Kapton during elongation

uniaxial tensile test was performed on Kapton sample (sized 15 mm width and 70 mm length). The maximum force applied during the uniaxial tensile test was adjusted to be in the elastic region of sample, being settled to 50 % of the yield strength measured previously, which resulted in a value of about 60 N. An electrical resistance of 1.4 Ω was measured before the test.

The relation between force and elongation (as well as the relation between stress and strain) was measured and is presented in Fig. 3.

The aluminum film did not visually present any signs of rupture. The electrical resistance was also measured during the experiment, presenting a linear increasing variation with strain (Fig. 4). The final value obtained after the test was only about 0.5 % higher than the initial value.

3.2 Textile materials

Textile materials were submitted to a tensile test driven to material rupture, in order to calculate its mechanical properties. The tensile test was performed on a Hounsfield HSK100 dynamometer and the thickness of the textile material was obtained using a digital thickness gauge M034A according to ISO 5084; the results are presented in Table 3. Kapton was also measured as a reference material. Table 3 also shows the initial electrical resistance of the film after aluminium deposition.

The materials that obtained the lowest electrical resistance values were samples C and E with average resistance values below 5 Ω. Samples B and D are non-conductive indicating a possible interface problem between the aluminum film and substrate surface. These samples showed a

Table 3 Results of mechanical tests

Sample	Width (mm)	Length (mm)	Thickness (mm)	E [Gpa] young module	ε_y (%) elongation at yield strength	σ_{ult} (Mpa) ultimate tensile strength	ε_{ult} (%) elongation at ultimate tensile strength	Resistance (Ω) after aluminum deposition
Kapton	30	27	0.05	2.50E + 00	9	345	80	1.4
# A	30	50	1.38	1.00E − 02	1.8–2.0	19	61	13.6
# B	30	50	1.17	5.00E − 03	6.8	16.4	81.4	$>10^6$
# C	30	50	0.41	4.00E − 01	5.0–6.0	59	35	0.8
# D	30	50	0.5	5.00E − 03	21	5.9	378	$>10^6$
# E	30	50	0.7	4.50E − 03	75	8.8	246	3.1
# F	30	50	0.58	5.00E − 04	10	10.8	733	9.2

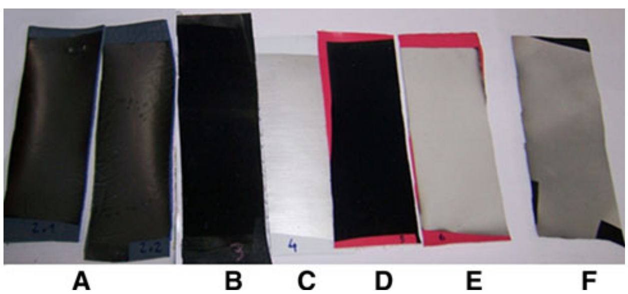

Fig. 5 Textile substrates with aluminum deposited

dark aluminum surface colour instead of the usual metallic look of aluminum film (Fig. 5).

The results from the tensile test indicate two types of textile materials regarding mechanical properties. In one group highly elastic materials are found: samples D, E and F. Regarding substrate samples E and F, although being conductive right after deposition, it was not possible to test them in tensile tests, as the handling of the samples to place them in the dynamometer was enough to damage the conductive film and render it non-conductive. This can be explained by the low stiffness of the textile substrate material. Stiffer substrates avoid the localized extension of the deposited film minimizing cleavage and other distortions of the aluminum film [26–28].

A second group of materials with higher stiffness and closer to Kapton were identified as materials A and C (although the Young module is still substantially lower than in Kapton: 2.5 GPa against 0.01 and 0.4 GPa for sample A and C respectively). Taking in account both electrical resistance and mechanical properties, uniaxial tensile tests were performed on samples A and C. All the other were eliminated either because of being non-conductive or due to their low yield strength. The tests were confined to the elastic regions of the substrates using a similar approach as for the Kapton samples, and the Kelvin method was used to measure electrical resistance variation. The conditions of the tensile test and sample characteristics are presented in Table 4 and the result in Fig. 6.

Table 4 Uniaxial tensile test parameters (samples A and C)

Sample	A	C
Substrate material	Synthetic leather	Textile double coated PVC screen
Conductive Film	Al (~300 nm)	Al (~300 nm)
Width [L] (mm)	30	30
Length [l] (mm)	70	70
Thickness [t] (mm)	1	0.25
Cross Section [Lxt] (mm^2)	41.4	12.3
Test speed (mm/min)	1	1
Load cell (N)	5000	5000
Fmax (N)	34	130
Electrical resistance before test (Ω)	13.6	0.8

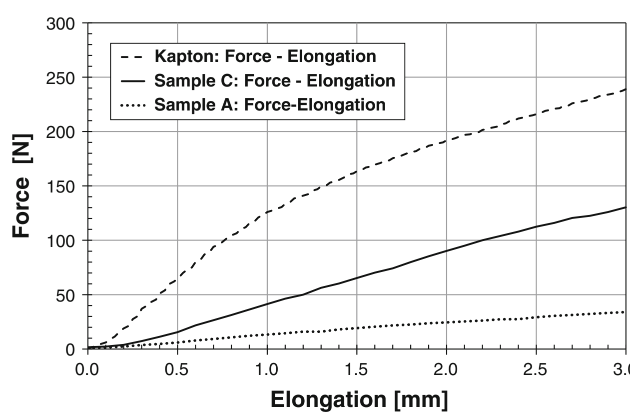

Fig. 6 Force—elongation Kapton versus textile materials, without aluminum coating

Comparing the mechanical behaviour of the textile materials against the Kapton reference, it can be observed that to achieve an extension of 3 mm of the Kapton sample 250 N are needed; for the double coated PVC textile screen

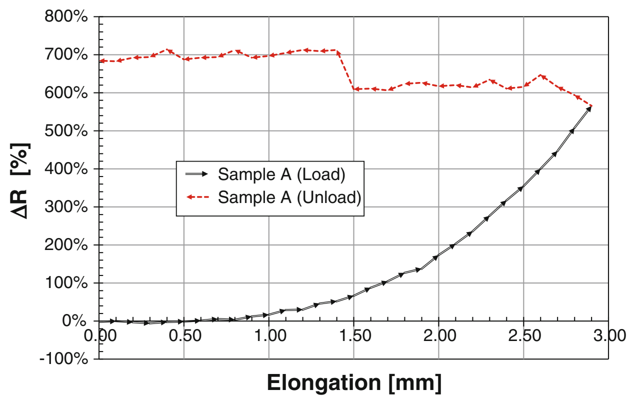

Fig. 7 Electrical resistance variation during tensile test (*sample A*)

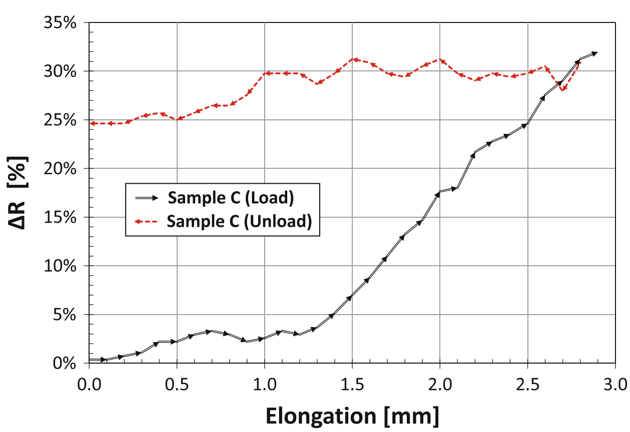

Fig. 8 Electrical resistance variation during tensile test (*sample C*)

Table 5 Cyclic tensile test parameters (sample C.1)

Substrate	Woven textile with PVC coating on both sides
Conductive Film	Al (∼300 nm)
Width [L] (mm)	30
Lenght [l] (mm)	70
Thickness [t] (mm)	0.25
Cross Section [Lxt] (mm2)	12.3
Test speed (mm/min)	2
Load cell (N)	500
Fmax (N)	100
Extension cycle amplitude	0 mm–2 mm–0 mm
Cycle number (n)	60
Test time (min)	∼120
Initial electrical resistance before test start	0.8 Ω

(sample C) 125 N; and for the artificial leather (sample A) about 40 N are needed. Material C achieved interesting results with a relation of force/elongation of 40 N/mm for a cross section of 12.3 mm^2. The material is flexible and

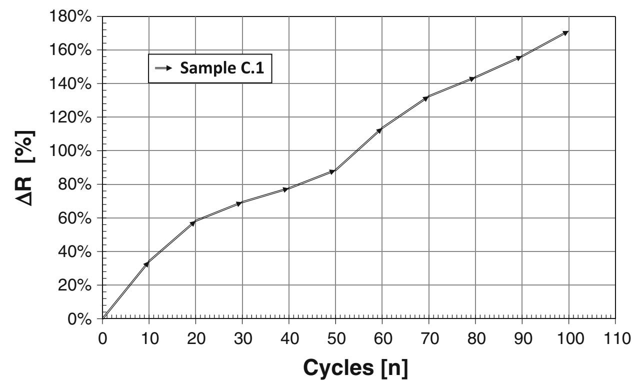

Fig. 9 Electrical resistance variation during cyclic tensile test (*sample C.1*)

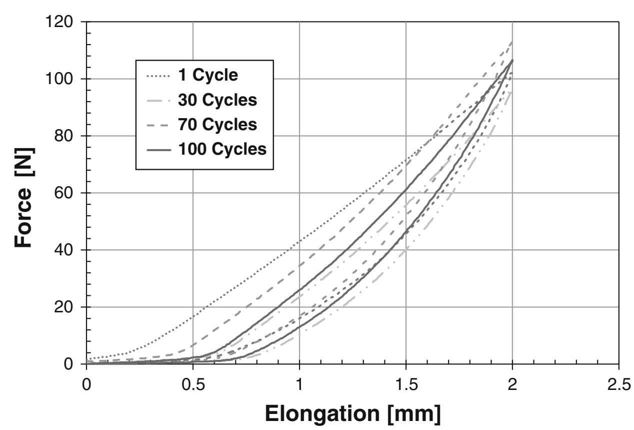

Fig. 10 Force—elongation during 60 cycles of tensile test (*sample C.1*)

presented low electrical resistance of the deposited film (<0.5 Ω/30 mm). PVC has also excellent dielectric properties and the textile surface can be used as dielectric between conductive lines. The behaviour of the electrical resistance variation is quite different for both textile materials and is presented in Figs. 7 and 8.

Sample A (synthetic leather) has a resistance variation of 700 % between start and end of the extension test. The aluminum film has a linear behaviour until 0.75 mm of extension equal to an applied force of 20 N.

Sample C had a total resistance variation of 25 % having a linear behaviour until 1.25 mm of extension for an applied force of 50 N. In this linear region the total resistance variation is about 5 % which represents only a 15 m Ω increase.

Recalling the test performed on Kapton, results of which are presented in Fig. 4, it can be concluded that there is a significant difference of behaviour between these materials. On one hand, the resistance change in Kapton is linear in the whole range, and on the other, electrical resistance values recover linearly when the sample is unloaded, returning to a value that is almost equal to the initial value. This can be

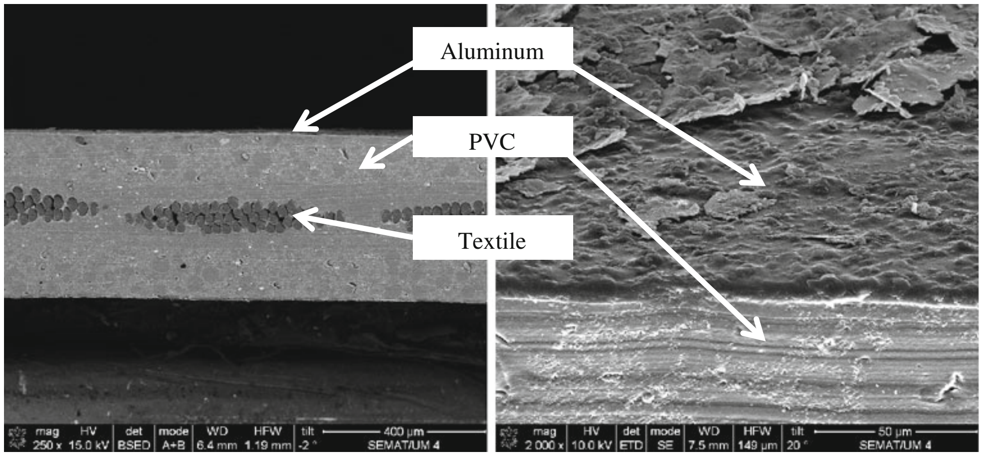

Fig. 11 *Left* cross section SEM photo of sample C, *right* aluminum film on sample C surface

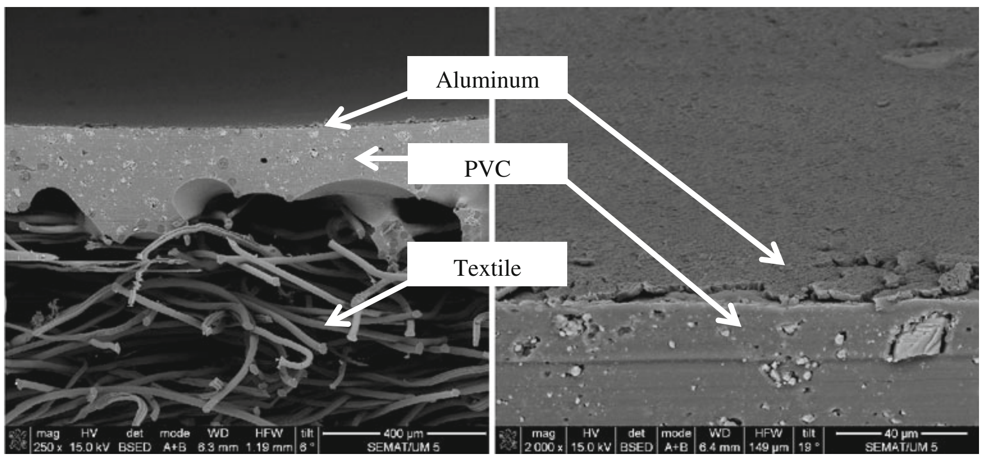

Fig. 12 *Left* cross section SEM photo of sample D, *right* aluminum film on sample D surface

explained by permanent deformation occurring in the textile substrate: considering that the aluminium layer is supported by the textile, it acquires the same deformation.

Another sample of the same material (sample C.1) was prepared and tested on a cyclic extension test. A summary of the sample characteristics and test parameters is presented in Table 5. Results obtained in this test are presented in Figs. 9 and 10.

The results show that the electrical resistance grows with the increasing number of cycles. After 100 cycles it is about 170 % higher than the initial value. Although the relative value is quite high the nominal value of the resistance after the test is only 1.4 Ω against 0.8 Ω at the beginning of the test.

Plotting the relation between force and elongation through the cyclic tensile test it is possible to observe a clear trend of the curves moving to the right side of the chart with increasing number of cycles. For the same applied force the extension gets higher with the increase of the number of the cycles indicating permanent strain of the sample.

SEM and EDX analysis were performed on sample C in order to evaluate chemical composition and aluminum film continuity on the substrate surface; Sample D, non-conductive, was analysed to evaluate chemical composition and aluminum film properties on the substrate surface.

In sample C, a continuous aluminum film over the substrate surface is observed. The cross section image shows the aluminum thin film above one of the coated sides of the textile screen as well as the textile yarns perfectly located on the centre of the PVC coating. The structure of this substrate with the yarns well protected by the PVC coating can be suitable for lithographic processes. These types of semiconductor processes use chemicals and it is very important that the fibres are kept dry—the surface permeability is key to allow its use [29, 30].

During the tests sample C and C.1 presented a weak adhesion to the substrate, which can be explained by some aluminum delamination on the surface, visible in (Fig. 11b). Chemical analysis by EDX shows aluminum, oxygen, carbon, silicon and chlorine. Carbon and chlorine indicate the coating material PVC. Analysing the SEM images of sample D (Fig. 12), it is possible to confirm that the sample presents a continuous film on the surface, both on surface and cross section pictures. A possible explanation for the non-conductivity of this sample after deposition is the oxidation of the aluminum film after deposition. This sample presents a ratio of oxygen to aluminum of about 5:1. Oxygen is also the main chemical component.

4 Conclusions

This work studied the influence of the substrate of deposited conductive patterns in Kapton and textile or similar materials. Aluminum films (300 nm thick) were deposited on several textiles with resistivity below $100 \times 10^{-9}\ \Omega$ m on the best samples.

From the experiments performed, it is possible to conclude that textile materials with low elasticity and uniform polymeric coatings, namely PVC, may be interesting flexible substrates for integration of electronic circuits or fabrication of sensors. A double coated PVC textile screen (sample C) was selected as the best textile substrate among tested samples. Cyclic tensile tests demonstrate acceptable resistivity changes (<180 %), due to plastic deformation. However, the interface between the metal and polymeric/textile substrates needs more research and testing to improve adhesion of the conductive material. Elastic textile materials showed not to be suitable flexible substrates for thin film deposition. The low stiffness conducts to localized elongations of the thin deposited films making the samples non-conductive.

It is desirable that electronics in textiles conform to the inherent textile properties which are flexibility and conformability. Both of these can be fulfilled by the PVC-coated materials studied here. Elasticity would have been an additional advantage and has to be studied in future work.

Although the materials studied are of common use in textile applications, they are not suited to be used directly as the base material for garments, as they do not provide comfort. But they would be easily integrated as carriers of the electronic system, without compromising the nature of the textile product.

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